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The opinions and conclusions expressed are the authors' and are not necessarily those of Texas SDHPT and FHWA.

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Abridgment

Minimum Delay Optimization of a Maximum Bandwidth Solution to Arterial Signal Timing

EDMOND CHIN-PING CHANG and CARROLL J. MESSER

ABSTRACT

This study indicated the advantages and drawbacks of combining the two major state-of-the-art traffic signal control strategies: the bandwidth maximization procedure and the delay minimization technique. The enhanced reduced-delay optimization model provided in PASSER II-84 guarantees minimum total arterial system delay within the slack-time allowance range of the original PASSER II-80 maximum progression solution. Modifications to the PASSER II signal timing plan for an arterial street system, using both a maximum bandwidth procedure and a minimum delay signal timing optimization algorithm, are evaluated. An efficient and usable delay-based search algorithm to assist traffic engineers in selecting a minimum delay arterial street signal timing plan that optimizes phasing sequence, cycle length, and offsets based on maximum bandwidth calculations in an urban network is demonstrated. The maximum bandwidth procedures are based mainly on calculations of distance, travel speed, and continuity of available green time for progressive movements without direct relationship to delay. The minimum delay algorithm minimizes total system delay endured by all traffic in the analysis network. Resulting offsets confirmed the feasibility of minimizing delay by the optimal offsets from the maximum bandwidth algorithm. When minimum delay and maximum progression are used, as calculated by the enhanced PASSER II-84, an improved level of service results thereby providing maximum progres-

sion and minimum total system delay within the offset slack-time range. This research has provided various insights into the operational characteristics of the enhanced PASSER II-84. It was found that PASSER II-84 consistently outperformed PASSER II-80. A consistent and satisfactory trend of delay reductions was found between PASSER II-84 and NETSIM evaluations. Recommendations are to implement the enhanced PASSER II-84 with possible field validation, to develop alternative strategies for allocating directional bandwidths, and to explore execution time and program efficiency.

This study evaluated the modifications to PASSER II-84 for an arterial street system using both a maximum bandwidth procedure and a minimum delay algorithm (1-6). The objectives were to devise a new delay optimization mechanism and to develop an experimental design for validating, evaluating, and comparing the enhanced PASSER II-84 and the existing PASSER II-80. Specifically, the study demonstrated an efficient and usable delay-based search algorithm to assist traffic engineers in selecting a minimum delay arterial traffic signal timing plan that optimizes the arterial offsets based on the optimal maximum bandwidth solution.

DELAY MINIMIZATION

A major task was to add a system offset optimization routine to the basic PASSER II program (1,7). The new extensions began by fine tuning the offsets from an existing progression solution using only straightforward approaches. The PASSER II-84 minimum delay optimization is designed to (8) minimize total arterial system delay as function of the offset at each signalized intersection. It is subject to (a) cycle length, (b) green split, (c) phase sequence, and (d) slack-time allowance of the optimal PASSER II-80 time-space diagram where the available slack-time allowance is the through green time, for a particular direction at each signal, that the offsets could be adjusted without losing the optimal progression bandwidth. This formulation is shown in Figure 1. At first, the input is given by geometric, traffic, and traffic signal control characteristics. The objective function is constructed according to constraints from the maximum bandwidth solution. Finally, the constrained optimum solution set is obtained by iteration using the modified system offset optimization-modified "sectioning" method (8).

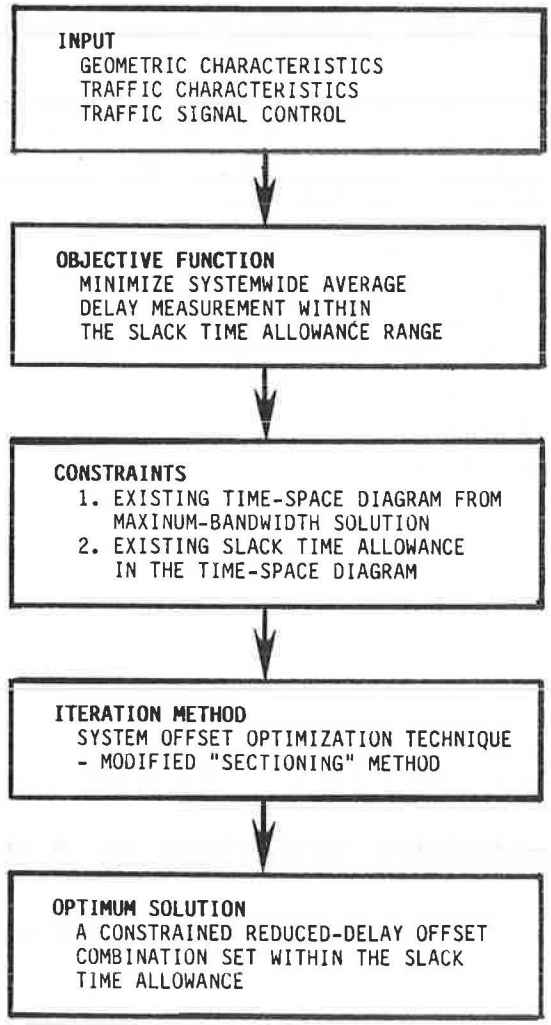

FIGURE 1 Formulation of constrained offset optimization problem.

PASSER II-84 OPERATIONS

Using the PASSER II-80 optimal time-space diagram as the starting solution and constraint, the PASSER II-84 optimization routine first identifies the offset slack-time allowance range to determine the possible optimum offsets for each intersection in the study arterial network. Then, the offset optimization algorithm starts a search within the slack-time allowance range for each intersection from the lowest possible optimum offset while keeping all the other intersection offsets constant. When the minimum arterial system delay is found within the slack-time allowance of a particular signal by simulating the system operations in PASSER II-84, the search will continue onto the next intersection until no further reduction of the total arterial system average delay value of this iteration can be found.

The major benefit of this systemwide offset optimization technique is that the objective function always remains the search for minimizing total arterial system average delay when performing the offset fine-tuning optimization within the slack-time allowance constraints. The optimization algorithm is constantly fixed at "system optimization," instead of at "local optimization" from link-to-link delay-offset analysis.

EVALUATION

Because actual traffic fluctuates, the NETSIM simulation program (9) was selected for its ability and complexity in changing traffic signal timing to achieve specific experimental conditions for field validation. As shown in Figure 2, the test procedure followed a straightforward analysis. First, the experimental plan was developed. Then, simulation techniques were used to enumerate the results of

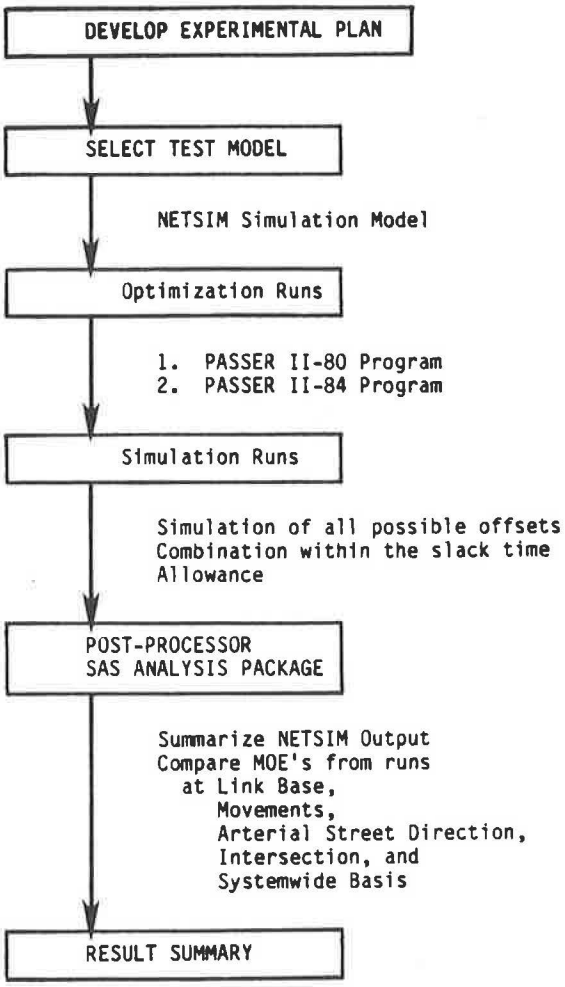

FIGURE 2 Evaluation of solution methodology.

arterial traffic signal systems. By measuring the systemwide measure of effectiveness (MOE), mainly delay and stops, at the end of the simulation study period, the operational performance of traffic on each segment in the analysis network can be evaluated. The simulation at first evaluated the enhanced offset fine-tuning optimization by analyzing one detailed test case as described by Rogness (5). A subsequent analysis was performed to evaluate PASSER II-80 and PASSER II-84 using 13 test scenarios under good, fair, and poor progression operations (10,11). This was done to answer the following questions:

1. Did the reduced-delay system optimization algorithm find the minimum delay offsets within the slack-time allowance?
2. On the basis of the PASSER II-84 evaluation, did the PASSER II-84 model improve on the systemwide delay and stops of the existing PASSER II-80 model?
3. On the basis of the NETSIM evaluation, did the PASSER II-84 model improve on the existing PASSER II-80 model?

Link Delay-Offset Analysis

An example of the NETSIM simulation analysis (summarized by SAS) for comparing the measures of effectiveness from different offset combinations either inside or outside the slack-time allowance ranges is shown in Figure 3. The horizontal axis is the offset value for intersection 2, in seconds. The vertical axis represents the average total systemwide delay per vehicle, in seconds per vehicle. The two vertical lines mark the range of slack-time allowance for intersection 2. The PASSER II-80 solution, as simulated by NETSIM, is labeled "OLD" and the enhanced PASSER II-84 solution is represented as "NEW." Figure 3 shows the average delay versus relative offsets at intersection 2. The figure also shows the sensitive change of average delay or stop performance with respect to any of the three offsets of intersections 2, 3, and 4 in the systemwide delay-offset response space. It could be considered as slicing the objective performance curve by "sectioning" at that particular intersection offset.

Each small dot in the diagram represents one individual NETSIM run for a given cycle length and progression phase sequence and their effects--either inside or outside the allowable slack-time range for each traffic signal. The feasible solution sets with all the intersection offsets inside the slack-time allowance ranges are represented by the solid boxes. These 310 NETSIM simulation runs evaluated the possibly feasible or infeasible solutions that may be generated through existing PASSER II-80, enhanced PASSER II-84, or any other traffic signal timing optimization program.

The solid curved line is the approximated regression line of the relationships between the total systemwide average delay and the offset value of intersection 2 in the Skillman Avenue network. The numerical value on the curve is calculated by averaging the amount of average delay per vehicle with respect to the different offset combinations having that particular offset value on intersection 2. The dashed curved lines delineate the 95 percent confidence limits for mean prediction of the average delay per vehicle as estimated by the SAS package.

The optimum offset obtained by this constrained reduced-delay offset optimization is represented by the offset combination with the offset at that intersection of that value. The optimum offset set, in this particular case, moved from the PASSER II-80 solution of 26, 85, and 49 sec to the PASSER II-84 solution of 31, 83, and 49 sec for offsets at intersections 2, 3, and 4, respectively. Applying a similar analogical relationship, the NETSIM simulation results were evaluated in terms of the average stops per vehicle versus the relative offsets for intersections 2, 3, and 4.

For this particular problem, the constrained optimum offset set was the same whether minimum delay or minimum stop was used as the selection criterion. Both the systemwide delay and the stop measurements of the optimum solution obtained from the maximum bandwidth procedure by PASSER II-80 were improved by the reduced-delay fine-tuning optimization technique in the PASSER II-84 model. Not only was the systemwide average delay per vehicle reduced to the minimum value within all the feasible offset solutions, but the average stops per vehicle were also reduced to the minimum value among all the possible offset solutions either inside or outside the slack-time allowance ranges.

As shown in Figure 3, both the PASSER II-80 and the PASSER II-84 solutions have a lower MOE than do arbitrary offset searches within the slack-time allowance range. This comparison indicated the superiority of offset optimization as calculated by PASSER II-80 and PASSER II-84 using the offset fine-tuning optimization algorithm in the enhanced PASSER II-84.

Even though absolute magnitude differences did exist between the measures of effectiveness of PASSER II-80, PASSER II-84, and NETSIM, the evaluation based on the NETSIM simulation provided a

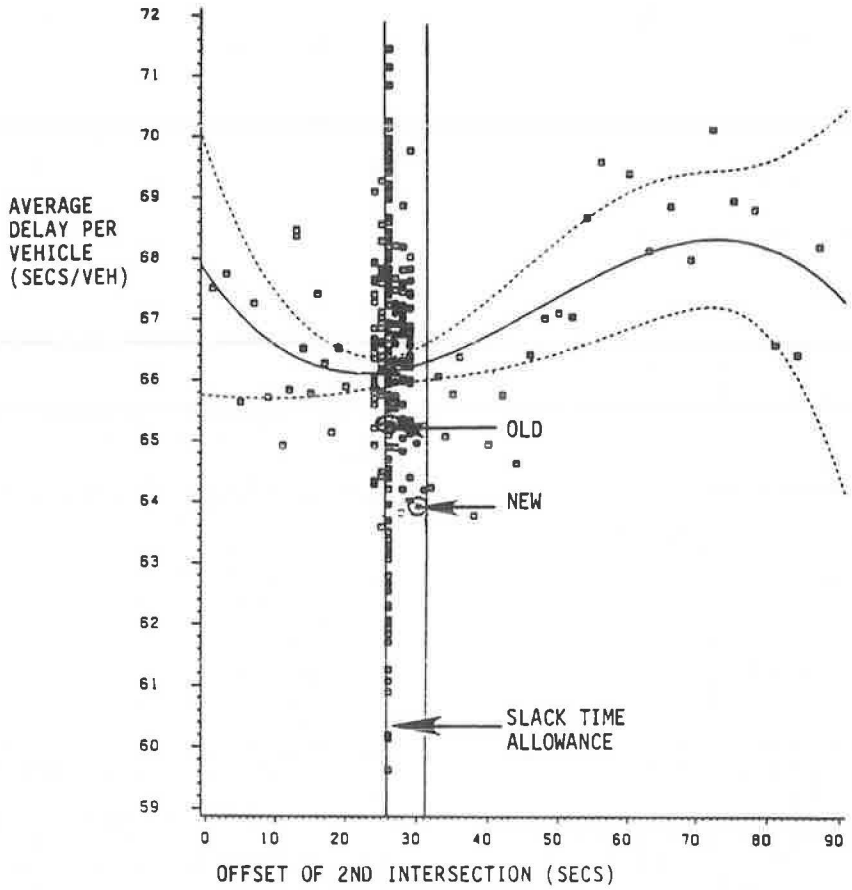

FIGURE 3 Summary of NETSIM simulation results—average delay per vehicle versus relative offset at intersection 2.

favorable examination of the system offset fine-tuning optimization algorithm developed for PASSER II-84. Several interesting results can be observed:

1. The reduction of average delay from PASSER II-80 (OLD OFFSET) to PASSER II-84 (NEW OFFSET) suggested that the offset fine-tuning optimization did reduce delay based on the original progression settings by the system offset optimization algorithm in PASSER II-84.
2. The minimum systemwide delay and stops may not always exist within the slack-time allowance range; they sometimes exist outside the allowable slack-time ranges based on the NETSIM evaluation.
3. The wide range of resultant total system MOEs from the NETSIM simulation analysis indicated sensitive interactions among the individual traffic signal timing parameters and the systemwide MOEs.
4. Difficulties exist in predicting the trend and magnitude of influence on the total systemwide MOEs if based only on the relative amount of change in the traffic signal offsets at any individual intersection.
5. Further reduction of average arterial system delay from the enhanced PASSER II-84 could possibly be obtained by moving to another offset combination outside the feasible slack-time allowance range.

Overall, the reduced-delay system offset optimization in PASSER II-84 found the signal offset solution with the minimum systemwide delay within the slack-time allowance of PASSER II-80 while not changing the optimum progression solution. In the next section the most significant results of the reduced-delay fine-tuning offset optimization in PASSER II-84, according to both PASSER II-84 and NETSIM evaluations, are summarized.

Performance Analysis

The NETSIM evaluation examined the robustness of the reduced-delay optimization under various test scenarios having different progression quality. To permit some range of progression efficiency while confining the number of alternatives, three spacings (full scale, half scale, and quarter scale) of the arterial were selected. The three cycle lengths

selected were 80, 90, and 100 sec, which appeared to be representative and still provided a nominal range of solutions. These NETSIM comparison runs were enumerated under 13 test scenarios, including the basic test case, with progression efficiency values ranging from 0.15 (poor progression) to 0.25 (fair progression), to 0.38 (good progression). These test arterial systems were selected so that the evaluation of the system offset optimization could be tested under various progression conditions. Figure 4 shows the systemwide average delay comparisons of PASSER II-80 on the horizontal axis versus PASSER II-84 on the vertical axis. Both PASSER II-84 and NETSIM evaluations are included. The consistent performance of PASSER II-84 over PASSER II-80 is identified by the locations of all the PASSER and NETSIM data on the lower side of the 45-degree line, which means that the enhanced PASSER II-84 calculated a consistently equal or lower delay than was calculated by the existing PASSER II-80. This result indicated that in some cases, even though the PASSER II-84 offset optimization could not find a lower system delay solution due to the limited slack time, it would still provide the original PASSER II-80 solution instead of a worse solution.

As shown in Figure 4, there are four possible results that both PASSER II-84 and NETSIM programs could possibly generate from PASSER II-84 and PASSER II-80 solutions. Quadrant I indicates that with both PASSER II-84 and NETSIM evaluations the average delay was reduced using PASSER II-84 compared with PASSER II-80; Quadrant III shows both PASSER II-84 and NETSIM evaluations and indicates that average delay was increased due to the use of PASSER II-84 for the PASSER II-80 original solution. Quadrants II and IV show the possible inconsistent results as evaluated by the PASSER II-84 and NETSIM programs. This figure indicates that the PASSER II-84 MOE provided a slightly higher estimation of the percentage of average delay reduction than did NETSIM but in an extremely consistent manner throughout all 13 test scenarios.

Summary

More than 310 NETSIM runs were made using the Skillman Avenue test bed. The detailed NETSIM analysis on this test case indicated that a reduced-delay solution could be found by PASSER II-84 among all the possible solutions including existing PASSER II-80, enhanced PASSER II-84, or any other signal timing program. The overall NETSIM simulation indicated that the system offset fine-tuning optimization can provide reduced delay and stops within the slack-time allowance range under all 13 NETSIM simulation test scenarios by trend analysis, binomial test, and paired t-tests. Figure 5 shows a summary of the percentage of systemwide delay reduction using the enhanced PASSER II-84 model with respect to the various progression efficiencies of the arterial progression systems used. This provided a basic indicator for estimating the possible systemwide delay reduction when the decision had to be made whether to implement the signal timing plan from the existing PASSER II-80 solutions or from the enhanced PASSER II-84 solutions. However, no specific trend of percentage of delay reductions versus progression efficiency could be observed.

The NETSIM analysis of average delay and stops on the link-to-link basis and total arterial travel direction indicated mixed results. That is, when the total arterial system delay is fine tuned based on the PASSER II-84 progression solution, the delay measurement may decrease on some links and increase on other links. The NETSIM analysis also indicated the difference that exists in total arterial system delay and delay incurred just in the arterial travel directions.

FINDINGS AND RECOMMENDATIONS

The maximum bandwidth procedures are based mainly on calculations of distance, travel speed, and continuity of available green time for progressive

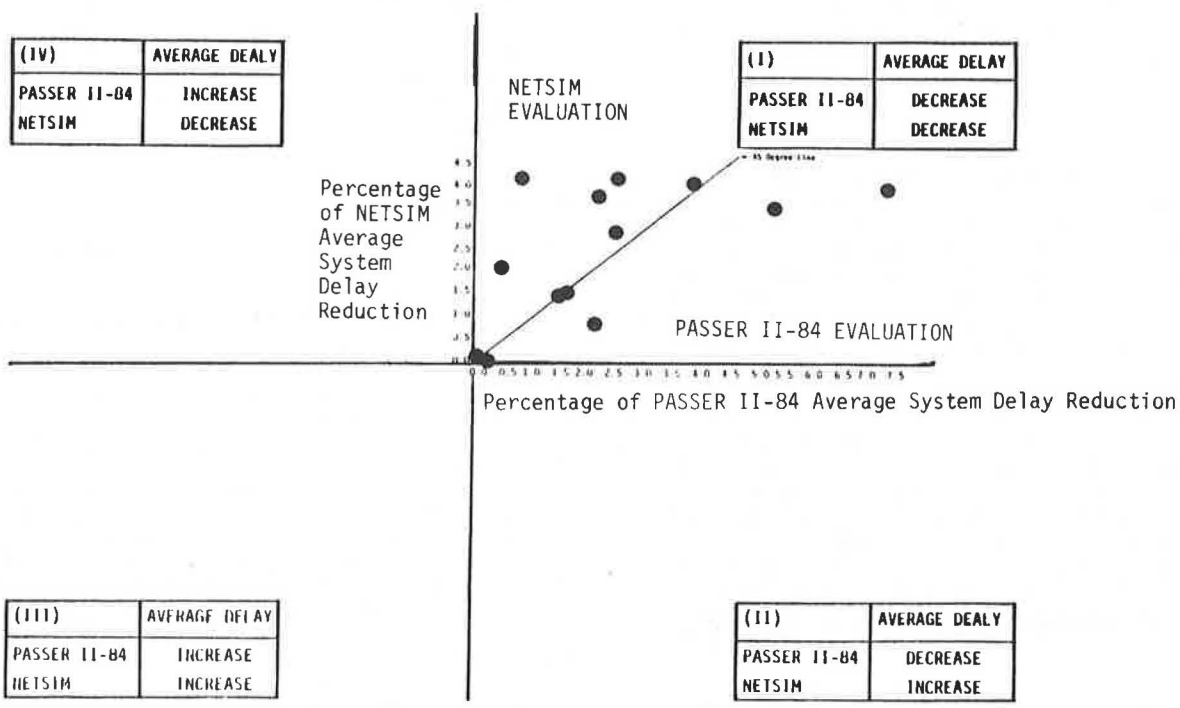

FIGURE 4 Comparisons of percentage change of average system delay in PASSER II-84 solutions and PASSER II-80 solutions as evaluated by PASSER II-84 and NETSIM programs.

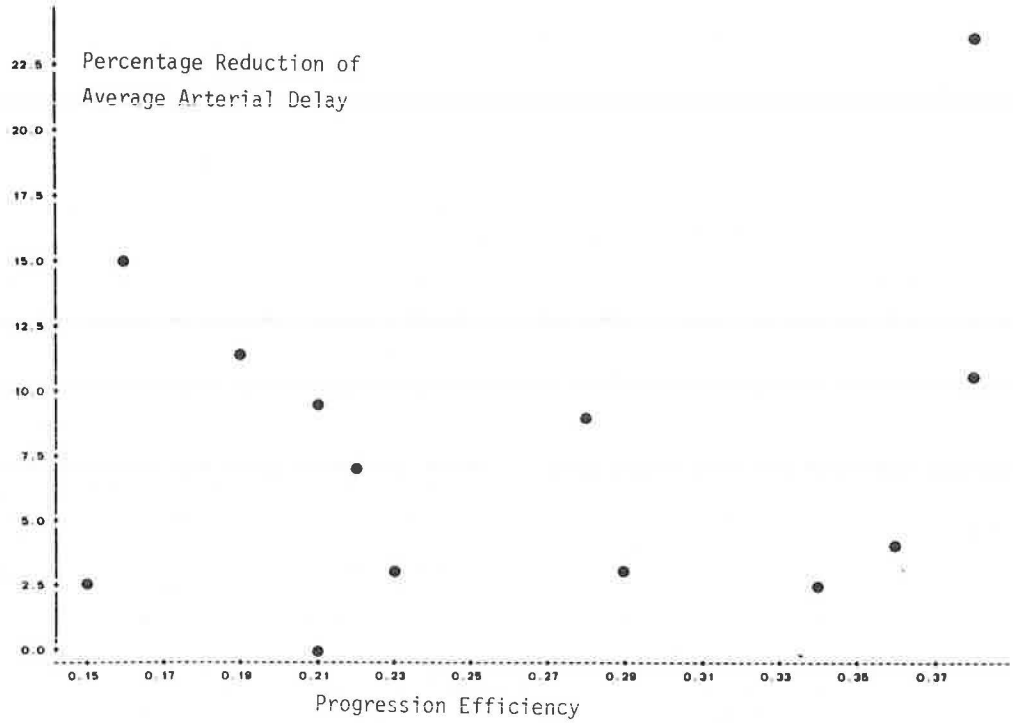

FIGURE 5 Comparisons of reductions in NETSIM average arterial delay per vehicle of PASSER II-84 solutions over PASSER II-80 solutions versus progression efficiency.

movements without direct relationship to delay. The minimum delay algorithm minimizes total system delay endured by all traffic in the analysis network whether there are progressive movements or not. The overall result offsets confirmed the feasibility of minimizing delay by the optimal offsets from the maximum bandwidth algorithm. When minimum delay and maximum progression are used, as calculated by the enhanced PASSER II-84, an improved level of service results thereby providing maximum progression and minimum total system delay within the offset slack-time range.

Findings

This study provided various insights into the operational characteristics of the enhanced PASSER II-84. It indicated the advantages and drawbacks of combining the state-of-the-art bandwidth maximization procedure and the delay minimization technique. However, the general improvement by PASSER II-84 relies primarily on the quality of the original PASSER II-80 solution. Several findings were obtained from this research:

1. PASSER II-84 consistently outperformed PASSER II-80 on the basis of two evaluations of delay as the measure of effectiveness. These delay evaluations were performed by the deterministic delay simulator found in PASSER II and by the unbiased microscopic delay simulator in NETSIM.
2. Consistent and satisfactory trends in the prediction of delay were found between PASSER II-84 and NETSIM. PASSER II-84 predictions of delay reduction, however, were somewhat higher than those derived from NETSIM.
3. PASSER II-84 solutions reduced total system delay from 0 to 4 percent for the 13 test scenarios. Arterial movement delays were reduced from 0 to 23 percent. These findings are based on NETSIM simulation using PASSER II-80 progression solutions as the base condition.
4. No apparent correlation was found between average arterial system delay reduction and progression efficiency. The amount of delay reduction possible depends heavily on the available slack-time allowances and on the efficient use of green time for progressive movements.
5. Instead of using the total directional traffic volume ratio and minimum green time constraint alone to provide the best directional bandwidth weighting, an optimization search outside the existing slack-time allowance ranges can further reduce the total arterial system delay by slightly varying the optimal progression solution.

Recommendations

As a result of this research, five recommendations are made:

1. The enhanced PASSER II-84 model should be implemented to further improve arterial traffic signal system operations.
2. Field validation of the reduced-delay offset-optimization algorithm to confirm the benefits yielded by the enhanced PASSER II-84 should be undertaken.
3. If minimum system delay is the most important objective for a particular arterial traffic signal system, the optimization search outside the existing slack-time allowance ranges is suggested. This is done by slightly varying the optimal progression solution to further reduce total system delay.
4. Alternative strategies should be developed for allocating the directional bandwidths to determine the best directional bandwidth weighting for minimizing total system delay.
5. This study did not explore the question of execution time and program efficiency. Benchmark

tests to examine the run time efficiency of the enhanced PASSER II-84 versus the existing PASSER II-80 on different computer systems are recommended. Developing possibly more efficient program architecture for PASSER II-84 to optimize calculation and eliminate duplicated FORTRAN coding is also recommended.

ACKNOWLEDGMENTS

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Analysis of Traffic Network Flow Relations and Two-Fluid Model Parameter Sensitivity

JAMES C. WILLIAMS, HANI S. MAHMASSANI, and ROBERT HERMAN

ABSTRACT

Presented in this paper is a systematic exploration, using microscopic simulation, of the sensitivity of network-level traffic flow descriptors and relationships, particularly those of the two-fluid theory of town traffic, to network features, traffic control, and traffic-interfering urban activity levels. Moving traffic interference, which is represented by stochastic short-term lane blockages of varying duration and frequency, is shown to be a key determinant of the traffic character of an urban street network and of the behavior described by the two-fluid theory and verified operationally. In addition, the sensitivity of the two-fluid model parameters to a change in traffic control strategy, in this case the coordination of signals to achieve progression, is demonstrated. Furthermore, keeping the same network configuration, the effect of network topology on traffic flow is examined by changing the identical length of the links.